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Determination of radial quantum dot position in needle nanowires from far-field measurements

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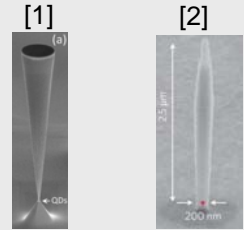
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I. Tapers for single-photon sources

- Quantum dots embedded in tapered nanowires have been shown as good candidates for realising an efficient single-photon source [1,2].
- For optimal efficiency the quantum dot should be placed on-axis. In this work we want to develop, a method for determining the quantum dot position in the nanowire based on the far-field emission pattern. The modelling is done using an open-geometry Fourier modal method [3], and a near-field to far-field transformation [4].



II. Modes and spontaneous emission rates in a nanowire

- The coupling of the quantum dot to the optical modes depends on the radial position of the quantum dot.
- Interference between the HE11 and TE01 modes leads to different power distributions in the NW, that should be visible in the far-field.

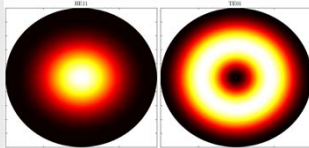


Figure 1: Mode profiles for the HE11 and TE01 modes.

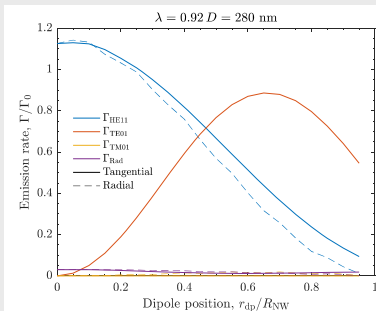


Figure 2: Spontaneous emission rate for a dipole in a nanowire.

III. oFMM and near-field to far-field transformation

- Field is expanded on eigenmodes:
- $$E(r, \phi, z) = \sum_{n,j} a_{nj}(r) E_{nj}(r) \exp(in\phi) \exp(i\beta_j z)$$
- Eigenmodes are expanded as a Fourier integral – open BCs:
- $$E_{r,nj} = i \int [b_{nj}^E(k) J_{n+1}(kr) - c_{nj}^E(k) J_{n-1}(k)] k dk$$
- Far-field is computed as:

$$E_{\theta,nj,\text{far}} \approx -\frac{ik_0 \exp(-ik_0 r)}{4\pi r} (L_{\phi,nj} + \eta N_{\theta,nj}),$$

where,

$$N_{\theta,nj} = 4(-i)^n \pi \cos \theta \cos n\phi \sum_m \Delta k_m (b_{mjn}^H - c_{mjn}^H) \delta(k_m - k_0 \sin \theta)$$

$$L_{\phi,nj} = 4(-i)^{n-1} \pi \cos n\phi \sum_m \Delta k_m (b_{mjn}^E + c_{mjn}^E) \delta(k_m - k_0 \sin \theta)$$

IV. Far-fields for needle structure

- Measured far-fields for needle with $D_{\text{Bot}} = 182 \text{ nm}$ (to be confirmed) and $\text{NA} = 0.75$.
- Simulated far-fields with $D_{\text{Bot}} = 200 \text{ nm}$, have good agreement with measurements.
- Cut-off for TE01 mode is at $d/\lambda = 0.23$, interference is still present – how?

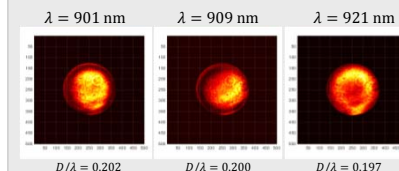


Figure 3: Measured far-fields for three different quantum dots.

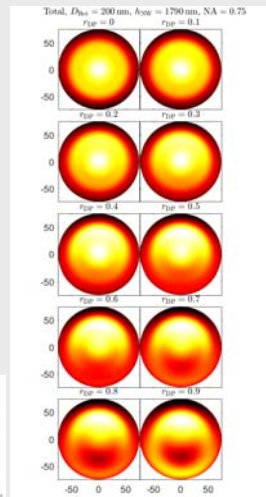


Figure 4: Simulated far-fields, where $D/\lambda = 0.22$

V. Radiation mode or guided mode?

- The guided modes exist as radiation modes just before they are guided.

Guided modes: $k_0^2 \leq \beta^2 < (nk_0)^2$
Radiation modes: $0 \leq \beta^2 < k_0^2$
Evanescent modes: $\beta^2 < 0$

- These semi-guided radiation modes will interfere with the guided HE11 mode, and only slowly escape the nanowire.
- A simple 2-mode model is therefore not enough.

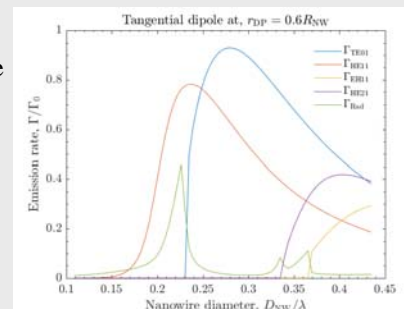


Figure 5: Spontaneous emission rate for a dipole in a Nanowire placed $0.6 R_{\text{NW}}$ off axis.

[1] Stepanov, P. et al., "Highly directive and Gaussian far-field emission from "giant" photonic trumpets," Appl. Phys. Lett. 107, 141106 (2015)

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[4] C. A. Balanis, Advanced Engineering Electromagnetics (Wiley, 1989), vol. 1, chap. 6